

Black Boxes Beget Blind Spots

Draft of paper submitted for IEEE Transactions
Disseminated among stakeholders, April 2004
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Surges Happen!

Significance

Part 6: Tutorial, Textbooks, and Reviews

The theme of this paper is that in an attempt to provide “fair” testing of any manufacturer’s surge-protective devices (SPDs), these SPDs should be subjected to the same test regimen, regardless of their design. Practical limitations on the number of specimens that can be tested over the range of stresses might then lead to missing a particular value where performance or failure mode might be unacceptable – a blind spot in performance as well as a blind spot in test procedures.

This paper has been developed with the contribution of field and laboratory data showing that past and present (up to 2004) test standards do leave blind spots in their test regimens, thus the need to re-examine these standards.

The paper is also an input to a “Reality Checks Initiative” aiming at revisiting several other issues in the development of SPD application and test standards:

- Counter the present upward auction for ever-higher surge current ratings
- Inject a sense of reality and cost-effectiveness in a runaway marketing-driven trend
- Avoid “red herring” importation of irrelevant data from IEC TC81 lightning parameters
- Focus on the real problem: TOV-induced failures are much more prevalent than surge-induced failures
- Correct the absence of mandates for provision of disconnectors that should be free from blind spots

BLACK BOXES BEGET BLIND SPOTS: Pitfalls to avoid in testing SPDs

François Martzloff
Draft 15 March 2004

Abstract — A tutorial presentation of the current situation on testing surge-protective devices (SPDs), in particular some unresolved issues on their application, with the corresponding call for action and cooperation among standards-developing organizations, SPD manufacturers, and SPD end-users.

I. INTRODUCTION

A. Background and Motivation

A long-standing philosophy, perhaps even a doctrine, in the approach to testing surge-protective devices (SPDs) is that test specimens should be seen as “black boxes” – meaning that all brands of devices should be treated alike, regardless of their internal design. Such an approach is commendable for the sake of “fairness” and is understandably motivated by concerns that a testing organization should not customize its test regimen to produce results that would favor one design while deprecating another design.

Meanwhile, given the practical limitations of testing a “reasonable” number of specimens over the wide range of possible stress threats, some test standards attempt to specify only a limited number of stress levels that appear “realistic,” but which can leave blind spots in characterizing the performance of the device.

This situation is not just an intellectual concept; this paper presents some examples of field failures or laboratory tests that occur for stress conditions that were not identified in the test regimen recommended or mandated by the current relevant product standard(s).

This paper is primarily concerned with qualification tests performed at independent laboratories to evaluate functionality of SPDs from a safety standard perspective (mainly from the UL 1449 Standard perspective [1]). The motivation for this paper is that there are several blind spots, as defined below, in SPD qualification tests performed at independent laboratories under the present standard procedures.

B. Testing surge-protective devices

Development of any product, including SPDs, involves several types of tests along the life cycle of the product, each with a specific purpose, as defined in IEEE standards:

design tests – Those tests made to determine the adequacy of the design under normal conditions or under special conditions ... (IEEE C62.11)

production tests – Tests made for quality control by the manufacturer on every device or representative sample ... (IEEE C37.20)

qualification tests – These tests subject a sample or samples to specified conditions designed to simulate normal, abnormal ... conditions [This is only a note from the IEEE definition for the nuclear power plant context]¹

diagnostic tests – Comparative tests or measurements of one or more characteristic parameters ... (IEEE C37.10)

II. BLACK BOXES

A. A refresher on terminology and definitions

Because this paper is tutorial in nature, a brief perusal of existing IEEE definitions² should facilitate the discussions, avoid confusion, and ensure common understanding of the terms:

black box – A system or component whose inputs, outputs and general function are known but whose contents or implementation are unknown or irrelevant. Contrast: glass box.

blind spot – A limited range within the total domain of application of a device, generally inferior to the maximum rating. Operation of the equipment or of the protective device might fail in that limited range despite the device's demonstration of satisfactory performance at maximum ratings.

functional testing – Testing that ignores the internal mechanism of a system or component and focuses solely on the outputs generated in response to selected inputs and execution conditions. Synonym: black-box testing.

glass box – A system or component whose internal components or implementation are known. Synonym: white box, Contrast: black box.

white box – See: glass box.

B. Forthcoming new definitions

Ongoing discussion among working groups concerned with this subject have produced a set of other terms that have not yet been recognized as official definitions but, as a group, reflect possible approaches to a more viable treatment of test specimens and more likely to avoid the pitfall of leaving blind spots undetected:

opaque box – Same concept as the existing definition of “black box.”

translucent box – Basic design of the device contents is known, but details are not.

transparent box – Synonym of the existing definition of “glass box” (without the unfortunate connotation of glass fragility, or the contradiction of white box as a synonym of glass box – white is not transparent.

¹ With the exception of nuclear power plants, qualification tests are not defined in industrial standards. The SPD manufacturer might perform some tests to prove that new product meets certain requirements, but usually trying to fulfill mandatory test conditions defined in the standards of their particular industry.

² These definitions are excerpted from IEEE Std 100-1996, now published as “IEEE 100™ The Authoritative Dictionary of IEEE Standard Terms”

III. MORE ON BLIND SPOTS

A. Terminology

The term “blind spot” in the context of SPD testing first appeared in IEEE Std C62.45TM-1987 as the authors of that document were keenly aware of the possibility that for some intermediate stress conditions, the SPD might not perform as expected, in spite of demonstrated satisfactory operation at maximum stress. One long-standing definition of that term, which appears in Webster’s as “An area in which one fails to exercise understanding, judgment, or discrimination” provides a good perspective to the context of surge testing: a lack of understanding how the device works (as in black-box testing) can indeed lead to not recognizing blind spots in the domain of application of the SPD. Supporting the skepticism about black-box testing philosophy, Webster mentions that lack of judgment (unquestioned application of a blanket procedure) can also lead to blind spots.

This term of blind spot is now being extended to the arena of testing, not just for performance of the protective function, but also for failure mode testing. If a test regimen fails to ferret out a region where an unacceptable failure mode can occur, we now say that there is a “blind spot” in that test regimen, thus implying a secondary definition of that term.

Blind spots in surge-protective devices, the general subject of this paper, generally result from the transition in the operation among internal components that respond in a different manner, depending on the parameters of the applied stress. An example of blind spot in the SPD performance can occur in the transition of the operation from a voltage-limiting device to a voltage-switching device (in the same package or in combination of two separate packages). An example of blind spot in the test regimen is the occurrence of an unacceptable failure mode at the transition from a fast-acting to a slow-acting overcurrent disconnecter, allowing higher energy deposition during a mid-range fault that endures, compared to the potentially higher energy deposition for a large fault but which is promptly cleared by the SPD disconnecter.

With the added knowledge of the principle of operation of the SPD as well as details on the component characteristics, a test laboratory and the agency requesting the tests have a much greater likelihood of successfully anticipating where in the range of possible stresses a test blind spot might occur, and therefore focus on that range of stress.

In a non-adversarial test program, the manufacturer is also in a good position to share the experience gained in the design stages and thus offer recommendations to the laboratory for test levels that would indeed focus on the crucial parts of the range where transitions might occur between the operation of one internal component to another. During the design stages, a manufacturer can be expected to thoroughly explore the range of stresses to which an SPD might be exposed, and make the appropriate design adjustments to prevent the occurrence of a blind spot, which might otherwise have been overlooked if only the test regimen mandated by the present standards had been applied.

B. The quest for blind spots

As a result of the two meanings of “blind spot” we need to differentiate between the two:

- A blind spot in the surge-protective function;
- A blind spot in the demonstration(s) of acceptable failure modes.

Blind spots in the protective function have by now been recognized and are not the subject of much debate. For instance, the protective function of a hybrid SPD package that includes a voltage-switching device, a decoupling inductance, and a voltage-limiting device might not work at some intermediate ranges of surge current, or with slow rising surges because the inductive drop expected from the decoupling inductance is insufficient to sparkover the voltage-switching device. As this type of test is nondestructive, it can be easily repeated on the same specimen over the wide range (matrix) of waveforms and amplitude levels. Hence, the phenomenon is well recognized and has been described at some length in the IEEE Recommended Practice on Surge Testing [2].

In recent years, recognition of temporary overvoltages (TOV) as the most likely cause of SPD failures, rather than excessive surges, has considerably increased. This recognition is quite apparent in the inclusion of guidance on the occurrence of TOVs for recent standards whose primary scope is describing the occurrence of surges (and were expected by some members to exclude consideration of TOV issues), for instance IEEE C62.41.1TM [3]; IEC 62066 [4], and UIE Guide Part VI [5]). However, these new standards do not include much guidance on testing the performance of SPDs under TOV conditions. To be meaningful and realistic, a test scenario intended to produce failure of the test specimen under such a TOV condition must stipulate a well-defined level of available fault current to be delivered by the power system to the failed specimen.

That is where the issue of blind spots in the test regimen, and blind spots in the performance of the disconnecter (if any) becomes the subject of the present debate in the intense quest for selecting suitable available fault current values that have a chance of ferreting out the blind spots in what might otherwise appear to be reassuring set of acceptable failure mode demonstrations.

Some SPDs returned from the field as in-service failures have an appearance quite different from that obtained by laboratory testing under TOV conditions suggested or mandated by the present standards. Examples of such discrepancies are given later in this paper. Such a discrepancy then raises the old question of how a test regimen is expected to “duplicate” field conditions by “realistic” testing, or whether a test should be performed on the basis of arbitrarily (but still intelligently) stipulated stresses. This problem has caused, and still causes intense debates in the field of surge testing: waveforms and amplitudes have been set in standards by a consensus process based sometimes on very limited field data.

An example of that debate occurred in the development of the so-called “SPD Trilogy” when addressing the case of a direct lightning flash to the building of interest [2], [3], [6]. A similar debate has now emerged on the subject of realistic TOV testing – with the added complication that the position of blind spots within the range of available fault currents is presently more a matter of consensus than of hard facts.

IV. EXAMPLES OF BLIND SPOTS

The following ten photographs showing examples of failure modes of cord-connected or hard-wired SPDs, communicated to me as anecdotal information for the purposes of this paper, illustrate the concerns about blind spots in earlier as well as present standardized test procedures. Six of these examples deal with consumer-type plug-in or cord-connected SPDs, the other four with hard-wired SPDs. These four sources of data are gratefully acknowledged for providing me with real-world examples, but please note that I have no intention to pin blame on a particular product, only to illustrate that the problem is real. For this reason, the photographs of the plug-in SPDs shown here were selected so as not to be readily identifiable as a particular brand.

A. Blind spots in performance and testing of cord-connected SPDs – EPRI PEAC tests

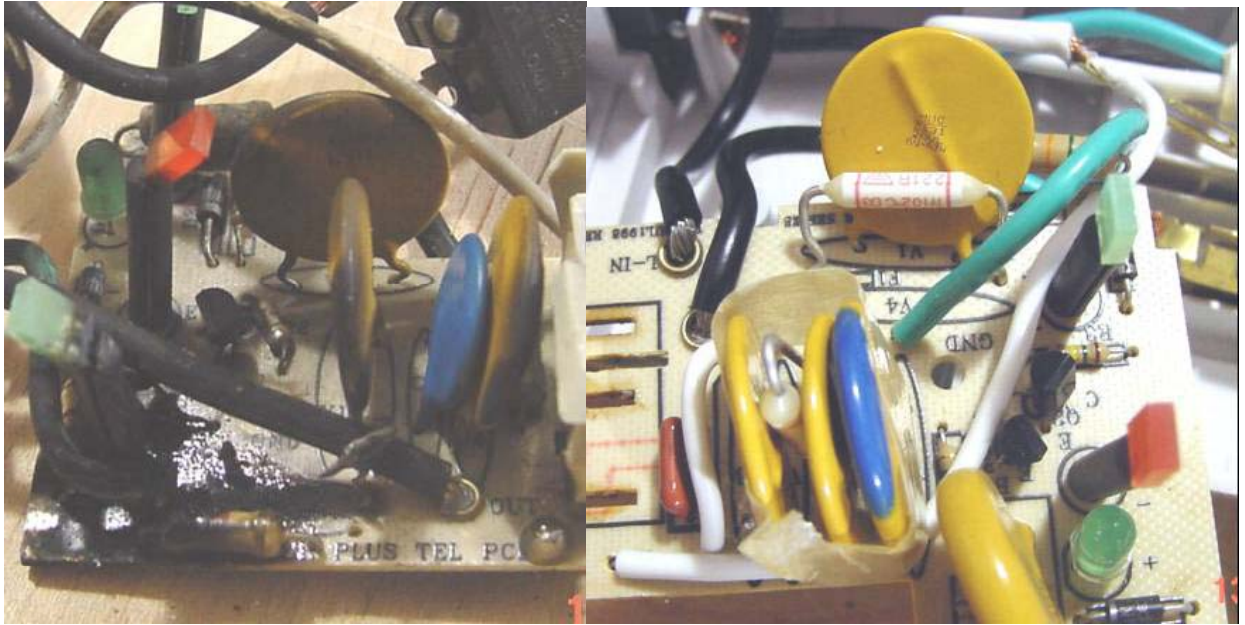
Figure 1a shows an example of a UL-listed SPD (UL 1449 First Edition) that failed in the field, with an unacceptable manner after exposure to a lost-neutral TOV. The available fault current at that site was not determined. Figure 1b shows an example of TOV failure induced in the laboratory during exposure to 170 % of normal voltage (a typical lost-neutral scenario) with an available fault current of 10 A – a level that would not trip a typical 15 A breaker.



Figure 1
Examples of TOV-induced failure modes on SPDs listed per UL 1449 First Edition
(Courtesy EPRI PEAC Corporation)

Growing awareness of this type of failure mode was one of the motivations for the development of the Second Edition of UL 1449 that now includes a regimen of tests with a range of available fault currents under abnormal voltage conditions.

As a result of the new edition of UL 1449, some design changes were made in existing products that were found in laboratory tests to fail the new requirements. Figure 2a shows an example of a pre-1449 Second Edition TVSS that failed in an unacceptable manner when subjected to the limited-current test per UL 1449 Second Edition. Figure 2b shows the same but redesigned SPD in which the addition of a thermal cut-out made the failure mode acceptable. Thus, evolution of UL 1449 into specifying additional available fault current values proved effective in enhancing the product safety, but there are still some blind spots in some 2002-vintage SPDs, as Figure 3 will show.



(a) Before redesign

(b) After redesign

Figure 2
Example of failure modes of an SPD before and after redesign
(Courtesy EPRI PEAC Corporation)

B. Blind spots in performance and testing of cord-connected SPDs – CPSC data

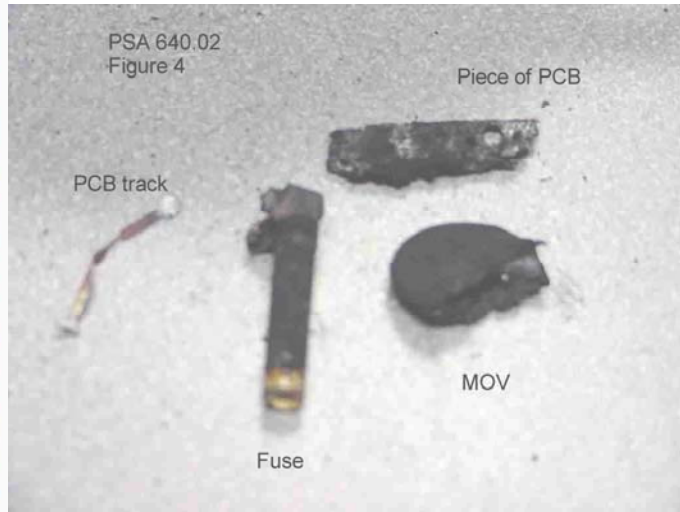
Figures 3a and 3b show two examples of cord-connected TVSSs that failed in the field and were then submitted to the Consumer Product Safety Commission (CPSC) for evaluation. Figure 3a shows the back of the enclosure of a seven-year old TVSS (pre-Second Edition of UL 1449) which was reported as having occurred upon recovery from a power system outage, a classic scenario of temporary overvoltage occurrences.

Figure 3b shows some components from a post-Second Edition of UL 1449 TVSS (production date code indicating 1999). The complete enclosure of that device (not reproduced in this paper because its brand would be easily recognizable), shows a hole and burn marks that would not be acceptable as “pass” in a UL 1449 test. The exact conditions of the system under which that failure occurred are not documented, but failure in a real-world environment did indeed occur.

Thus, real-world situations can occur in the field where some UL-listed TVSSs might fail in an unacceptable manner when exposed to TOVs for which the actual available fault current might not have been included in the present mandated test regimen.



(a)



(b)

Figure 3
Field failure specimens submitted for assessment
(Courtesy U.S. Consumer Product Safety Commission)

Ongoing laboratory tests at the CPSC indicate that commercially available, UL-listed TVSSs can experience unacceptable failure modes for TOV-induced failure in ranges not included in the present UL 1449 requirements for the available fault current. This situation indicates that there are some blind spots left in the available fault current range of the present test regimen prescribed by UL 1449, Second Edition.

C. Blind spots in performance and testing of hard-wired SPDs – CH data

A combination of the Cutler-Hammer (CH) data on field failure returns and laboratory diagnostic tests (as discussed in the paragraph “back-door definitions”) provides some further insights in the problems of black-box testing SPDs under an arbitrarily set range of available fault currents.

Figure 4a shows an example of in-field failure. There was no practical after-the-fact possibility of performing measurements of available fault current at that particular site, but a comparison with the results of hundreds of in-house laboratory tests led to the conclusion that the available fault current at this site was in the range of 5 A to 500 A. The laboratory test samples tested outside this range (below 5A fault currents and above 500A fault currents) have totally different level and type of damage. To simulate the same in-field conditions in the laboratory (a set of diagnostic tests) and obtain similar results, the operator provided a power supply with an available fault current of 100 A. This shows that the range for this test procedure, which did replicate the in-field conditions, is not covered in any of present UL 1449 standards tests.

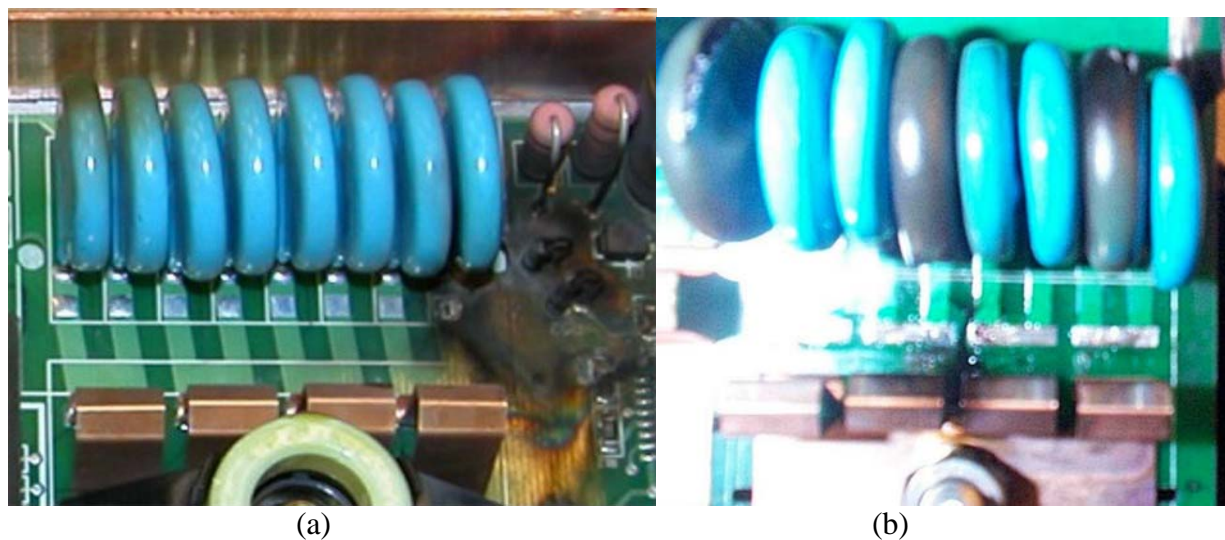


Figure 4
(Courtesy Cutler-Hammer)

Figure 4b shows an example of an SPD failed at 5 A fault current. Comparing the two Figures (4a and 4b) does show the differences between a failure mode test with 5 A available fault current – the presently prescribed UL1449 test – and a failure mode test performed with 100 A available fault. This example adds further strength to the point that some medium available fault currents must be included in SPD test requirements.

D. Blind spots in performance testing of hard-wired SPDs – Schneider Electric data

Figure 5a shows the results of a laboratory test performed on a new product under development to simulate an abnormal overvoltage test with an available short circuit current (I_{sc}) of 500 A. The hard-wired SPDs under test were designed and intended to be employed on the side of enclosures associated with 120/240 Vac service entrance load centers. The value of 500 A was intended to replicate conditions when the SPD would be employed in remote locations where the available I_{sc} from the local electric service provider was limited by the impedance in the long distribution circuits. The SPD might also be employed in locations where there would not be any secondary overcurrent protective devices. The only local overcurrent protective device might likely be the fused cutout on the primary of the local distribution class transformer. The use of a 500A represents an available I_{sc} that is not presently specified as a standard test in any edition of UL1449.

Figure 5b shows an example of one of several in-field failures in remote areas of the same rural coastal county. The available I_{sc} at the specific locations were greater than 100 A but less than 1000 A. This specific SPD was protected by 15 A fuses. The 15 A fuses were found intact and functional. However, the black phenolic cover of the SPD had been heated and was deformed from the internal heating. It was suspected that exposures to TOV conditions were major contributing factors in the in-field failures. The factory designs and construction of that specific model SPD was UL witness tested to the Second Edition of UL 1449. All UL tests had passed satisfactorily.



Figure 5
(Courtesy Schneider Electric)

E. Lessons learned

All these field returns and laboratory tests show that although UL has been performing safety tests for years, some types of failure have not been observed in the field, illustrating the need for ferreting out blind spots and better understanding of realistic TOV conditions.

IV. WHERE IS THE DISCONNECTOR ?

The critical function of an SPD disconnecter has not yet been sufficiently recognized although – with some hindsight – it should have been obvious. The seminal publication on metal-oxide varistors (MOV) applications (GE Transient Manual [7]) includes several pages discussing the need and details of “fusing protection” and yet some present standards (IEC 61643 series [8]; [9]) leave the stipulation of a disconnecter optional as internal or external while others (IEEE C62.34) do not provide any guidance on testing the disconnecter function.

It is now urgent that this ambiguity about disconnectors be replaced by appropriate guidance or even mandates in SPD application standards.

This lack of guidance on the need for a disconnecter function and the safety aspects of locating a poorly-defined so-called “Surge Arrester” within a building has also resulted in a controversy on the application of SPDs, in part due to the existence of two terms, “Surge Arrester” and “Transient Voltage Surge Suppressor” (TVSS). Interpretation of the NEC® from Article 280 and Article 285, respectively about where these SPDs may be installed has added complications – and thus a “blind spot” in guidance!

V. CONCLUSIONS

The present situation in the guidance – or mandates – for the application of surge-protective devices is leaving gaps – blind spots – in test procedures and qualification tests that cry for redemption, as illustrated by the five examples cited in this paper. Greater cooperation, coordination, and consultations among standards-developing organizations, manufacturers, and end-users is one approach that would bring positive results. While some progress has been made in that direction, the present situation still leaves several gaps that urgently call for action, as listed below:

A. The present situation

- Lingering perception that “black-box testing” is the desirable and “fair” test method
- Discrepancies between field failures and lab-induced failures observed under standard specifications
- Lack of consensus on what is a reasonable number of tests in ferreting out blind spots
- Insufficient knowledge of the range and values of real-world TOV scenarios
- Insufficient recognition of the function and location of SPD disconnectors

B. Recommended action items

- In a few words, but with much work implied, address all the concerns listed above!

VII. ACKNOWLEDGEMENTS

Over the forty years that I have been chasing transients – and they are still there to be caught – my research has been supported first by the General Electric Corporate Research and Development, and later by the National Institute of Standards and Technology. This research was motivated by the crying need for mitigation of surge effects, and encouraged by my colleagues – regretfully too many to enumerate – of the IEEE Surge-Protective Devices Committee and the Power Quality Coordinating Committee, as well as the IEC Technical Committee 77 on Electromagnetic Compatibility.

The contributions of anecdotal but real-world data by the four organizations identified with the photographs and narratives (EPRI PEAC, Consumer Product Safety Commission, Eaton/ Cutler-Hammer, and Schneider Electric) provided for me and – more important, for readers of this paper – valuable support for the “Black Boxes Beget Blind Spots” theme, and all are gratefully acknowledged.

VIII. REFERENCES

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